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Expansive and collapsible soil behaviour under the Revised Soil Classification System

Compportement des sols gonflant ou affaissants selon le Système Révisé de Classification des Sols

R. Ortiz-Hernández*, E. Rojas-González
Universidad Autónoma de Querétaro, Santiago de Querétaro, México
**raforther@gmail.com*

ABSTRACT: Identifying expansive and collapsible soils is crucial for geotechnical engineering. Grain size distribution and Atterberg limits help identify such soils, and the Revised Soil Classification System enhances this identification. It primarily introduces a new testing protocol for the liquid limit of soils using various fluids. When assessing the plasticity behaviour of these soils under different levels of chemical stabilization, it is evident that the concentration of the stabilizing agent linearly reduces expansion or collapse potential. However, the liquid limit's behaviour under varying pore fluid chemistry and stabilizing agent concentration follows a non-linear trend.

RÉSUMÉ: L'identification des sols expansifs et pliables est cruciale pour l'ingénierie géotechnique. La distribution granulométrique et les limites d'Atterberg aident à identifier ces sols, et le système révisé de classification des sols améliore cette identification. Il introduit principalement un nouveau protocole de test de la limite de liquidité des sols utilisant divers fluides. Lors de l'évaluation du comportement plasticité de ces sols sous différents niveaux de stabilisation chimique, il est évident que la concentration de l'agent stabilisant réduit linéairement le potentiel d'expansion ou d'effondrement. Cependant, le comportement de la limite liquide selon la chimie du fluide interstitiel et la concentration de l'agent stabilisant varie suit une tendance non linéaire.

Keywords: Expansive soils; collapsible soils; geotechnical characterization; soil classification.

1 INTRODUCTION

In geotechnical engineering, certain soils pose risks during infrastructure construction. These include expansive and collapsible soils. Qualitatively identifying these soils based on their index properties is crucial in engineering practice to prevent costly foundation repairs resulting from misidentification.

Expansive soils alter their volume with changing saturation levels, expanding when saturated and contracting during desiccation (Zepeda, 2004). They are primarily characterized by their mineral composition, with clay minerals like smectite and illite being significant (Mitchell & Soga, 2005). The relationship between clay mineralogy and their position on the Casagrande Plasticity Chart has been established (Okkels, 2019).

Figure 1 illustrates that montmorillonite clay and illite fall above the A-Line (distinguishing clays from silts) and below the U-Line (indicating empirical clay behavior), classifying them both as "high plasticity clay," CH, under the Unified Soil Classification System (USCS). The primary difference between them is the value of the plasticity index (PI).

Collapsible soils remain stable under dry conditions but experience significant volume changes (shrinkage) when saturated under the same load (Ali, 2011). Indications of a collapsible soil include low volumetric weight and a high void ratio. The relationship between its dry volumetric weight and liquid limit (LL) (Rezaei et al., 2012) or the void ratios under natural conditions and at the LL (Denosov, 1951) has been established.

In soil classification advancements, the "Revised Soil Classification System (RSCS)" has been developed. It involves a review of the test protocol regularly used in the USCS to describe the fractions controlling the soil's mechanical and hydraulic behavior (Park & Santamarina, 2017). The RSCS is summarized graphically in the flow diagram presented in Figure 2.

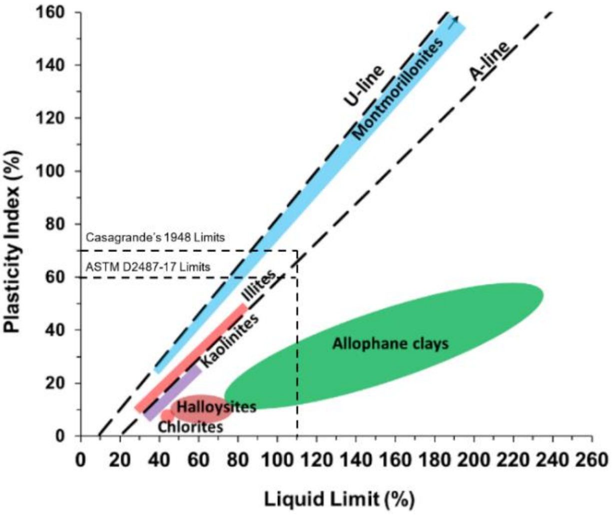
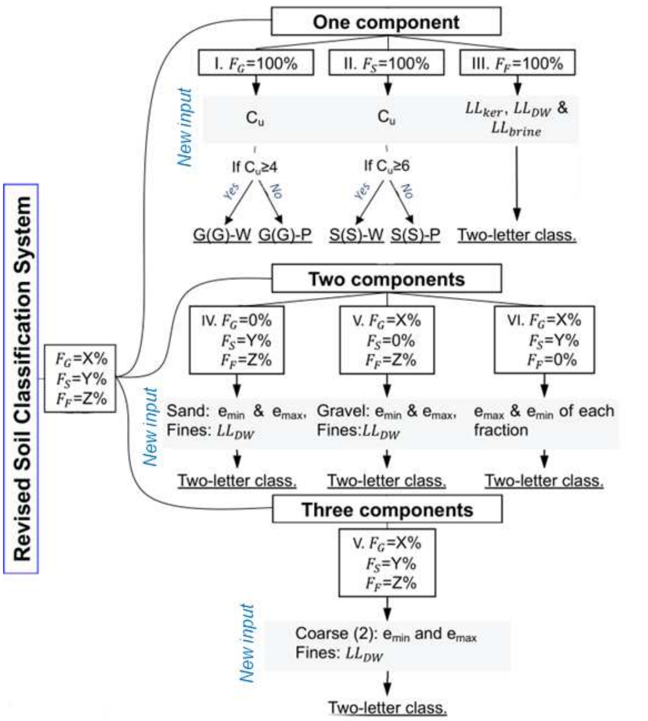


Figure 1. Fine-grained soils plasticity chart with mineralogy zones (adapted from Okkels, 2019).



Note:
- If the classification involves F or (F): include the classification of fines (column III)
- If the classification is G(G) or S(S): include grading information (columns I or II)

Figure 2. RSCS workflow (adapted from Castro et al, 2023).

For soils where the fine fraction influences the soil's mechanical and/or hydraulic behavior, the RSCS advises analyzing this fraction using the LL with various fluids. The LL is preferred due to its consistency, repeatability, and absence of segregation or edge effects (Jang & Santamarina, 2017).

The RSCS recommends using specific testing fluids: deionized water, enhancing double layer effects; kerosene, affecting van der Waals forces; and 2 M NaCl brine, causing the collapse of the diffuse double layer (Jang & Santamarina, 2017; Castro et al., 2022).

These fluid-based limits help establish relationships that express specific soil properties. The deionized water to brine water ratio denotes pore fluid permittivity, while the kerosene to brine ratio defines fluid electrical conductivity. These relationships lead to the determination of a new parameter called "Electrical Sensitivity" (Jang & Santamarina, 2017):

$$S_E = \sqrt{\left(\frac{LL_{dw}}{LL_{brine}} - 1\right)^2 + \left(\frac{LL_{ker}}{LL_{brine}} - 1\right)^2} \quad (1)$$

where S_E is the electrical sensitivity, LL_{dw} (%) is the deionized water LL, LL_{brine} (%) is the 2 M NaCl brine LL and LL_{ker} (%) is the kerosene LL.

When LL ratios are less than 1, their reciprocals are used to maintain a positive value in equation (1). To address density variations between kerosene (2) and deionized water and salt concentration in brine (3), these corrections are applied as outlined in Jang and Santamarina (2017):

$$\left.\frac{LL_{ker}}{LL_{brine}}\right|_{corr} = \frac{LL_{ker}}{LL_{brine}} \frac{1-c_{brine}\frac{LL_{brine}}{100}}{G_{ker}} \quad (2)$$

$$\left.\frac{LL_{dw}}{LL_{brine}}\right|_{corr} = \frac{LL_{dw}}{LL_{brine}} \left(\frac{1-c_{brine}\frac{LL_{brine}}{100}}{G_{ker}}\right) \quad (3)$$

where c_{brine} is the concentration of NaCl brine (mol/L) and G_{ker} is the specific gravity of kerosene.

The electrical sensitivity is a function of particle size, shape, mineralogy, surface, and edge charges, these in turn have an effect in the hydraulic conductivity, compressibility, and shear strength of the soil (Jang and Santamarina, 2016).

The electrical sensitivity and corrected brine LL are used in the RSCS Plasticity chart (Figure 3a), while the corrected LL ratios are depicted on a new electrical sensitivity chart (Figure 3b).

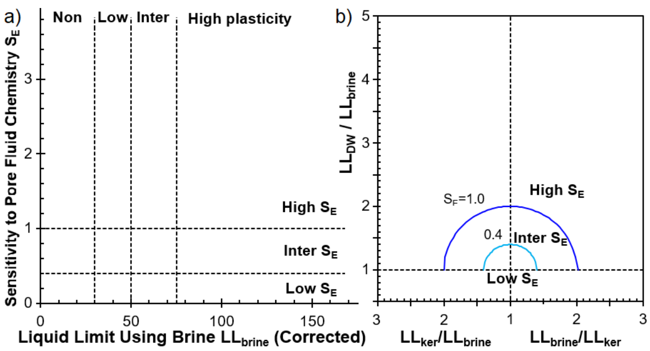


Figure 3.(a) RSCS plasticity chart and (b) electrical sensibility chart.

Tests using this new protocol reveal that soils with expansive minerals like montmorillonite exhibit high plasticity with brine and an elevated electrical sensitivity. These findings group them into distinct sectors on the Plasticity Chart and Electrical Sensitivity Chart (Figure 4).

As of now, collapsible soils have not undergone this testing protocol, and thus, their position on the Plasticity and Electrical Sensitivity Charts remains uncertain.

This research aims to correlate a soil's expansive or collapsible behavior with its electrical sensitivity parameter due to the lack of knowledge regarding how special soils behave in various pore fluid conditions, both natural and when stabilized.

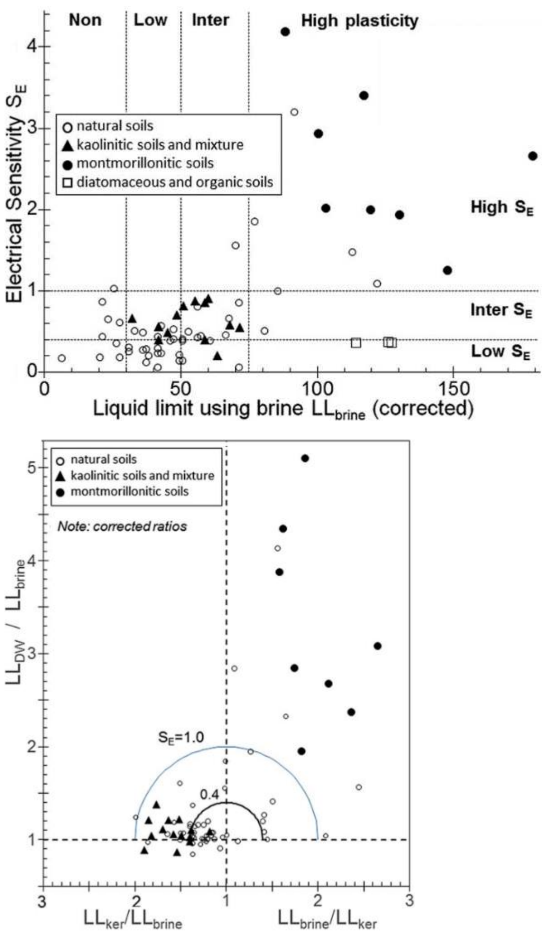


Figure 4. Soil mineralogy clusters in the RSCS plasticity and electrical sensitivity charts (adapted from Jang and Santamarina, 2017).

2 EXPERIMENTAL PROGRAM

The experimental program involved assessing a soil's expansion or collapse potential under natural conditions and applying a stabilizing agent at 3% and 5% concentrations while measuring electrical sensitivity. Additional tests for specific surface and specific gravity of soil solids were conducted to monitor material property changes.

The soil was dry sieved with a #200 sieve and dried at 60°C to prevent soil chemistry alteration (ASTM, 2010) before conducting expansion/collapse and LL tests.

The expansion potential was assessed using ASTM D4546-14 A-Method, while the collapse potential was determined following the ASTM D5333-12 standard. In both tests, the material was remolded to match the natural unit weight and water content reported by Verdín (2022) for expansive soil and Fonseca et al. (2014) for collapsible soil.

The electrical sensitivity parameter was calculated using the corrected LL ratios of the material with deionized water, reagent-grade kerosene, and 2 M NaCl brine using equations (2) and (3). The LL was determined using the fall cone method (BSI, 1990) and adjusted based on the fluid's concentration or specific gravity. To prevent material contamination, a fresh sample was used for each LL test and not reused between tests.

The 2 M NaCl brine is prepared by dissolving 117 grams of NaCl reagent in one liter of deionized water. Electrical sensitivity was calculated using the EGEL KAUST's spreadsheet for RSCS soil classification. Specific surface assessments for soils in their natural state and two stabilization levels were conducted with the "methylene blue" test (Santamarina et al., 2002), and the specific gravity of soil solids was determined following ASTM D854-10 standard.

3 RESULTS AND DISCUSSION

Chemical stabilization agents at 3% and 5% were employed, aligning with established practical geotechnical engineering ranges (Barma & Dash, 2022; Basma & Tuncer, 1992). Chemical stabilization was chosen due to its effectiveness in altering soil index properties, as other stabilization methods yielded less significant changes.

The soils used in these tests were previously identified as having expansion potential (Verdin, 2022) or collapsible behavior (Fonseca et al., 2014). Both soils primarily consist of fine particles. Key properties of the natural condition materials are detailed in Table 1.

Based on this data, both soils fall into the RSCS classification as F(F) soils, where the fine fraction governs the soil's mechanical and hydraulic characteristics. As a result, it's necessary to establish the LL of the materials using deionized water, kerosene, and brine as stated in the RSCS flowchart of Figure 2. The outcomes of the corrected LL tests are presented in Table 2, and their placement on the RSCS

Plasticity and Sensitivity Charts is depicted in Figure 5.

Expansion test results and electrical sensitivity data are displayed in the top section of Table 3, while potential collapse results and electrical sensitivity are presented in the lower section of the same table.

Table 1. Soil properties under natural conditions.

Material	Fractions			Atterberg Limits	
	G (%)	S (%)	F (%)	LL (%)	PL (%)
Expansive soil	0	16	84	76	39
Collapsible soil	0	3	97	63	39

Material	SUCS	Gs	Se (m²/g)
Expansive soil	CH	2.48	300
Collapsible soil	MH	3.15	27

Data obtained from Verdin (2022), Fonseca et al (2014) and the authors. G is Gravel, S is Sand, F is Fines, LL is Liquid limit, LP is Plastic limit, Gs is specific weight of soil solids, Se is specific surface.

Table 2. Liquid limits of soils under natural conditions and two stabilization levels in different pore fluid chemistry, electrical sensitivity and RSCS classification.

Material	LL_{dw} (%)	LL_{ker} (%)	LL_{brine} (%)	S_E	RSCS
Exp + 0%	67	41	46	0.47	F(F)-LL
Exp + 3%	66	46	46	0.32	F(F)-LI
Exp + 5%	63	49	50	0.29	F(F)-IL
Col + 0%	87	66	52	0.37	F(F)-II
Col + 3%	121	67	55	0.84	F(F)-IH
Col + 5%	109	61	60	0.54	F(F)-II

LLdw is LL with deionized water, LLker is LL with kerosene, LLbrine is LL with brine and S_E is Electrical Sensibility.

Table 3. Behaviour of expansive and collapsible soils under different stabilization levels.

Material	SP (kPa)	FSI (%)	S_E	Gs	Se (m²/g)
Exp + 0%	4.9	9.36	0.47	2.37	300
Exp + 3%	2.5	1.30	0.32	2.71	214
Exp + 5%	2.5	0.54	0.29	2.62	153

Material	CP (%)	S_E	Gs	Se (m²/g)
Col + 0%	4.61	0.37	2.76	27.07
Col + 3%	2.43	0.81	2.92	19.57
Col + 5%	1.50	0.54	2.92	17.13

SP is Swelling pressure, FSI is Free Swell Index, Gs is specific density of solids, SE is specific surface and CP is Collapse Potential Index.

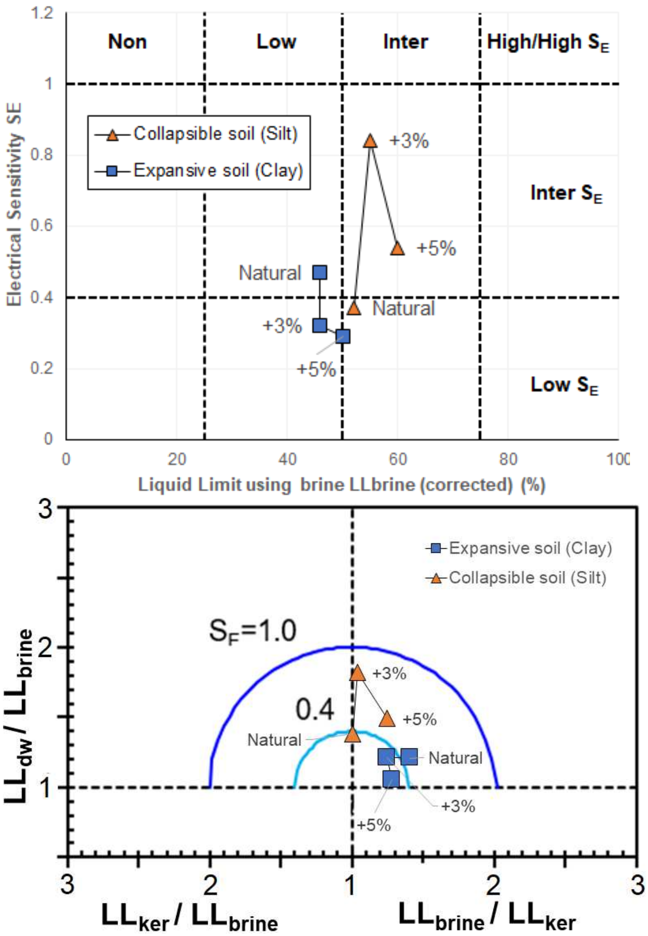


Figure 5. Evolution of the behaviour of expansive and collapsible soils in the RSCS plasticity and electrical sensitivity charts.

In the RSCS Plasticity Chart, expansive soils show that it has a natural low brine plasticity and low electrical sensibility, at a 3% stabilization agent concentration the soil presents a reduced electrical sensibility but no change in its brine plasticity, at a 5% stabilization the electrical sensitivity keeps decreasing but it presents an increase in brine plasticity. This effect could be attributed to the change lime produces on the ionic concentration of the soil and its effects on the double layers (Barman & Dash, 2022).

In collapsible soils, plasticity increases with greater stabilizing agent concentrations, however, in terms of electrical sensitivity there is a significant peak at a 3% concentration and a sharp decrease at 5%. The increase in deionized water and brine plasticity can be attributed to the microstructural mechanisms of hydration, surface deposition and shallow infilling of cementitious materials in the silt clusters (Basma and Tuncer, 1992).

In the Electrical Sensitivity Chart, expansive soils exhibit increased permittivity at 3%, followed by a reduction at 5%, with increased conductivity. Collapsible soils show reduced permittivity at 3% but increased permittivity at 5%.

No linear behavior was observed for both treated expansive or collapsible materials in both Plasticity and Electrical Sensitivity charts, so more experiments on higher concentrations are needed to establish a possible trendline, however these concentrations are purely for research purposes as these might be economically unfeasible for real-life applications.

In the complementary soil solid density measurements, the addition of the stabilizing agent increased the soil specific density, affirming a physical-chemical change in the soil's particles. As for specific surface, both lime and cement reduced the soil surface area with increasing concentration. Notably, the decrease in the collapsible silt surface area while the LL in both deionized and brine fluid increases during chemical stabilization suggests the presence of a distinct mechanism in the LL test, depending on the material's particle size and mineralogy, as noted by Sridharan and Prakash (2000).

During experimentation with the collapsible silt, an intriguing phenomenon occurred. It underwent a cementation reaction with both deionized water and brine, leading to an exothermic reaction with a temperature rise of 20°C, ultimately solidifying into a hard mass. To conduct the LL test, continuous stirring and fluid addition were essential to cool the mixture and prevent the formation of a non-workable paste.

Although the stabilization of these soils is a physical-chemical reaction that tends to continue to evolve over time, no significant change in LL results was recorded during the testing period of 14 days.

4 CONCLUSIONS

In the expansive soil, lime concentration inversely impacts expansion, with electrical sensitivity following a linear trend. However, brine plasticity exhibits a decreasing-then-increasing pattern.

For the collapsible soil, increased cement concentration reduces collapse potential. Electrical sensitivity displays a non-linear trend, while plasticity in brine rises with cement concentration.

In both cases, complementary tests reveal that chemical stabilization increases solids density and diminishes their specific surface area.

For establishing material expansive using RSCS, it's advisable to utilize its electrical sensitivity as a control parameter. However, for collapsible soils, finding a suitable control parameter remains challenging.

A potential issue with this new system is the contamination of soil samples with kerosene and brine. Proper disposal and treatment of test residues need to adhere to environmental regulations, a capability not commonly found in standard soil mechanics laboratories.

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